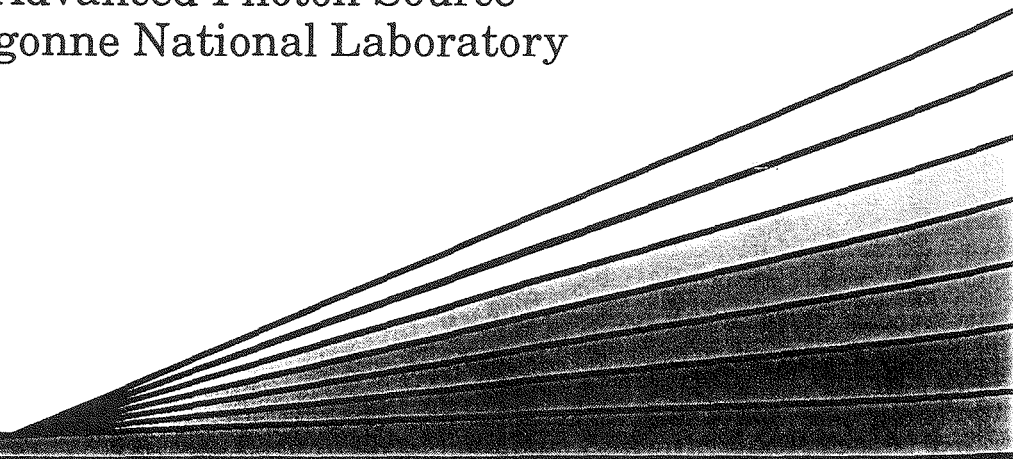


The Effect of Incident Angle on the Shielding Thickness for Secondary Bremsstrahlung

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Introduction

To provide suitable radiation protection at synchrotron beamlines it is necessary to shield for several different sources of radiation. One source of radiation is the secondary bremsstrahlung (SB) that is produced when the bremsstrahlung from the storage ring strikes a beamline component. The characteristics of the SB depends upon several factors, including the incident bremsstrahlung-beam spectrum and the composition and geometry of the target. However, for a target that is sufficiently thick for an electro-magnetic shower to completely develop, several simplifying assumptions may be made that allow for a relatively straightforward calculation of the necessary shielding.

A developed shower becomes mostly photons with an energy spectrum centered about the energy of the minimum attenuation coefficient, μ_{\min} , for the target material. For most materials, the energy of μ_{\min} , E_{\min} , is a few MeV. With the assumption of a fully developed shower, the SB emitted from a target can be approximated as a monochromatic beam with an energy of E_{\min} . Furthermore, if we assume that the material used for shielding will be Pb, we can use the value of E_{\min} for Pb for any SB independent of target. This assumption is somewhat conservative, but only increases the thickness of the shielding a small amount because the attenuation coefficient for Pb varies slowly in the range of 1-10 MeV.

Using the above assumptions, the calculation of shielding thickness for a given amount of SB is straightforward, providing the SB strikes the shielding at a normal incidence ($\theta = 90^\circ$). However, in many cases of interest, normal incidence is not the case and is not a good approximation. An example would be for a section of shielded beampipe immediately downstream of a bremsstrahlung collimator.

At ordinary x-ray energies (5 keV to 30 keV), it is common to use an effective thickness, so that

$$t_e = t / \sin \theta. \quad [1]$$

At showering energies (~10 MeV or greater in Pb), there is significant lateral scattering and it is clear that equation [1] is a poor approximation.¹ However, at energies of interest for SB (~5 MeV), it is not obvious what effect the angle of incidence will have upon the effective shielding.

In the rest of this paper, the results of simulations will be given for SB beams that are incident upon various thicknesses of Pb at several angles.

EGS4 Simulations

The EGS4 program was used to calculate SB transmission. Electron Gamma Shower (EGS4) is a Monte-Carlo code that simulates the coupled transport of electrons and photons with energies from a few keV to several TeV. It also consists of a stand-alone program PEGS4, which creates data to be used by EGS4 from cross-section tables for elements of atomic number 1 through 100. The EGS4 program is described in detail elsewhere.²

In the EGS4 calculation for this study, a photon of given energy is directed onto a slab of lead at the specified angle; then the photon and the products of its interaction with the lead are tracked. A sample of 10,000 incident photons was used for each condition in this study. The time to run the code for each case was approximately three hours on a Silicon Graphics Indigo workstation.

Results were obtained for Pb slab thicknesses of 8 mm, 12 mm, and 24 mm with incident photon energies of 1 MeV, 5 MeV, and 10 MeV (i.e., nine total sets of data). For each thickness/energy condition, incident angles of 5°, 15°, 30°, 45°, 60°, 75°, and 90° were examined. (In this study, 90° is normal incidence.) Below 5°, the statistics become very poor and no reliable information was obtained.

Results and Discussion

The results for the nine combinations of incident-photon energy and Pb-slab thickness are given in Tables 1-9. In these tables, I is the average trans-

mitted energy for one incident photon, I/I_0 is the transmitted energy normalized to the incident energy, and t_e^{Pb} is the effective thickness of Pb seen by the incident photon. The t_e^{Pb} values are calculated using

$$t_e^{Pb} = \frac{1}{\mu_{Pb}} \ln \frac{I}{I_0} \quad [2]$$

with the absorption coefficient μ_{Pb} being taken as 0.0688 cm²/g, 0.0426 cm²/g, and 0.0489 cm²/g for 1 MeV, 5 MeV, and 10 MeV, respectively.³ Figures 1-3 show I/I_0 for the three incident energies for each of the slab thicknesses. It is clear from these results that the angle of incidence has a significant effect on the amount of transmission for all of the energies studied. In all cases, the 5-MeV incident energy photons have the greatest transmission. Hence, the remainder of the discussion will focus on this case.

Figure 4 shows how the results from the EGS4 simulation ("I_{EGS}") compare to the values calculated with

$$I_{calc}/I_0 = e^{-\mu t/\cos \theta}. \quad [3]$$

Error bars have been omitted from Figure 4 to maintain clarity (they can be deduced from the relevant tables or from Figures 1-3), but it should be noted that the errors for the I_{EGS} at the lower angles are quite large. In Figure 4, a value less than one for I_{calc}/I_{EGS} indicates that the shielding is underestimated by I_{calc}. This is true for all values shown. The amount of underestimation ranges from ~10% for the angles between 45° and 90°, to considerably larger differences at 5°.

The underestimation of radiation transmission by equation [3] is due to the well-known "build-up" factor. The build-up factor occurs because photons emitted by Compton scattering have sufficient energy that they are not immediately reabsorbed and continue travel through the material (largely in the forward direction).⁴ The Compton scattered photons that make it through the slab contribute to the transmission energy. The EGS4 simulation tracks the Compton-scattered photons and consequently gives transmission values that more accurately reflect the scattering processes than equation [3].

Conclusions

The following statements can be made based upon the results presented above.

1. The amount of transmission of SB through a slab of Pb varies significantly with incident angle. It is appropriate in most cases to use this effect in shielding calculations.
2. The EGS4 simulations consistently give higher transmission results than a calculation using equation [3]. Shielding calculated with equation [3] should be adjusted to account for this difference.
3. For incident angles $\geq 45^\circ$, the transmission discrepancy between EGS4 and equation [3] can be assumed to be 10%.
4. Below 15° , the results given by EGS4 have very large errors and cannot be considered reliable. It would probably be prudent to use the results for 15° for all angles $\leq 15^\circ$.

References

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- ¹For more information on showering particles see: B. Rossi, *High Energy Particles*, Prentice Hall, Englewood Cliffs, NJ (1952).
 - ²W. R. Nelson, H. Hirayama, and D. W. O. Rogers, "The EGS4 Code System," SLAC Report 265, Stanford Linear Accelerator (1985).
 - ³J. H. Hubbell, "Photon Cross Sections, Attenuation Coefficients, and Energy Absorption Coefficients from 10 keV to 100 GeV," NSRDS-NBS-29, U. S. Dept. of Commerce (1969).
 - ⁴More information on the build-up factor can be found in: B.T.Price, C. C. Horton, and K. T. Spinney, *Radiation Shielding*, Pergamon Press, New York (1957).

Table 1 The Effect of Incidence Angle on Shielding: 1 MeV
Photon Energy and 0.8 cm of Thick Slab of Lead

Angle	I (MeV)	I/I_0	t_e^{Pb} (cm)
5°	0.00230 ± 0.028	0.0023 ± 0.028	7.82 ± 3.3
15°	0.107 ± 0.028	0.107 ± 0.028	2.88 ± 0.35
30°	0.307 ± 0.023	0.307 ± 0.023	1.52 ± 0.095
45°	0.407 ± 0.023	0.407 ± 0.023	1.16 ± 0.071
60°	0.506 ± 0.023	0.506 ± 0.023	0.878 ± 0.058
75°	0.553 ± 0.0057	0.553 ± 0.0057	0.763 ± 0.013
90°	0.568 ± 0.0057	0.568 ± 0.0057	0.7259 ± 0.013

Table 2 The Effect of Incidence Angle on Shielding: 5 MeV
Photon Energy and 0.8 cm of Thick Slab of Lead

Angle	I (MeV)	I/I_0	t_e^{Pb} (cm)
5°	0.258 ± 0.18	0.0516 ± 0.036	6.13 ± 1.8
15°	1.38 ± 0.18	0.275 ± 0.036	2.67 ± 0.27
30°	2.67 ± 0.14	0.534 ± 0.028	1.30 ± 0.11
45°	3.19 ± 0.14	0.637 ± 0.028	0.932 ± 0.092
60°	3.47 ± 0.14	0.693 ± 0.028	0.758 ± 0.085
75°	3.57 ± 0.036	0.715 ± 0.0071	0.694 ± 0.021
90°	3.56 ± 0.036	0.711 ± 0.0071	0.705 ± 0.021

Table 3 The Effect of Incidence Angle on Shielding: 10 MeV
Photon Energy and 0.8 cm of Thick Slab of Lead

Angle	I (MeV)	I/I_0	t_e^{Pb} (cm)
5°	0.64 ± 0.36	0.064 ± 0.036	4.95 ± 1.1
15°	2.56 ± 0.36	0.256 ± 0.036	2.46 ± 0.25
30°	4.85 ± 0.29	0.485 ± 0.029	1.30 ± 0.11
45°	6.24 ± 0.29	0.624 ± 0.029	0.851 ± 0.083
60°	6.86 ± 0.29	0.686 ± 0.029	0.680 ± 0.076
75°	6.92 ± 0.072	0.692 ± 0.0072	0.663 ± 0.019
90°	7.18 ± 0.072	0.718 ± 0.0072	0.596 ± 0.018

Table 4 The Effect of Incidence Angle on Shielding: 1 MeV
Photon Energy and 1.2 cm of Thick Slab of Lead

Angle	I (MeV)	I/I_0	t_e^{Pb} (cm)
5°	0.0004 ± 0.02	0.0004 ± 0.02	10.1 ± 5.0
15°	0.035 ± 0.02	0.035 ± 0.02	4.32 ± 0.82
30°	0.174 ± 0.016	0.174 ± 0.016	2.25 ± 0.12
45°	0.286 ± 0.016	0.286 ± 0.016	1.61 ± 0.071
60°	0.350 ± 0.016	0.350 ± 0.016	1.35 ± 0.058
75°	0.373 ± 0.004	0.373 ± 0.004	1.27 ± 0.014
90°	0.396 ± 0.004	0.396 ± 0.004	1.19 ± 0.013

Table 5 The Effect of Incidence Angle on Shielding: 5 MeV
Photon Energy and 1.2 cm of Thick Slab of Lead

Angle	I (MeV)	I/I_0	t_e^{Pb} (cm)
5°	0.305 ± 0.16	0.061 ± 0.032	5.78 ± 1.2
15°	0.786 ± 0.16	0.157 ± 0.032	3.83 ± 0.43
30°	1.85 ± 0.13	0.370 ± 0.025	2.05 ± 0.14
45°	2.48 ± 0.13	0.495 ± 0.025	1.45 ± 0.11
60°	2.91 ± 0.13	0.581 ± 0.025	1.12 ± 0.091
75°	2.98 ± 0.032	0.595 ± 0.0064	1.07 ± 0.022
90°	3.19 ± 0.032	0.637 ± 0.0064	0.931 ± 0.021

Table 6 The Effect of Incidence Angle on Shielding: 10 MeV
Photon Energy and 1.2 cm of Thick Slab of Lead

Angle	I (MeV)	I/I_0	t_e^{Pb} (cm)
5°	0.344 ± 0.29	0.0344 ± 0.029	6.07 ± 2.3
15°	1.33 ± 0.29	0.133 ± 0.029	3.63 ± 0.4
30°	3.26 ± 0.23	0.326 ± 0.023	2.02 ± 0.13
45°	4.70 ± 0.23	0.470 ± 0.023	1.36 ± 0.09
60°	5.51 ± 0.23	0.551 ± 0.023	1.07 ± 0.077
75°	5.65 ± 0.18	0.565 ± 0.018	1.03 ± 0.056
90°	5.87 ± 0.059	0.587 ± 0.0059	0.96 ± 0.018

Table 7 The Effect of Incidence Angle on Shielding: 1 MeV
Photon Energy and 2.4 cm of Thick Slab of Lead

Angle	I (MeV)	I/I_0	t_e^{Pb} (cm)
5°	$1.65 \times 10^{-5} \pm 0.0083$	$1.65 \times 10^{-5} \pm 0.0083$	14.2 ± 8.0
15°	0.011 ± 0.0083	0.011 ± 0.0083	5.81 ± 1.3
30°	0.037 ± 0.0066	0.037 ± 0.0066	4.25 ± 0.23
45°	0.0777 ± 0.0066	0.0777 ± 0.0066	3.29 ± 0.11
60°	0.126 ± 0.0066	0.126 ± 0.0066	2.66 ± 0.067
75°	0.154 ± 0.0017	0.154 ± 0.0017	2.41 ± 0.014
90°	0.165 ± 0.0017	0.165 ± 0.0017	2.32 ± 0.013

Table 8 The Effect of Incidence Angle on Shielding: 5 MeV
Photon Energy and 2.4 cm of Thick Slab of Lead

Angle	I (MeV)	I/I_0	t_e^{Pb} (cm)
5°	0.0329 ± 0.086	0.00658 ± 0.017	10.4 ± 2.7
15°	0.124 ± 0.086	0.0248 ± 0.017	7.65 ± 1.8
30°	0.625 ± 0.086	0.125 ± 0.017	4.3 ± 0.29
45°	1.02 ± 0.069	0.204 ± 0.014	3.29 ± 0.14
60°	1.47 ± 0.069	0.295 ± 0.014	2.52 ± 0.097
75°	1.64 ± 0.017	0.329 ± 0.0034	2.3 ± 0.022
90°	1.72 ± 0.017	0.345 ± 0.0034	2.2 ± 0.021

Table 9 The Effect of Incidence Angle on Shielding: 10 MeV
Photon Energy and 2.4 cm of Thick Slab of Lead

Angle	I (MeV)	I/I_0	t_e^{Pb} (cm)
5°	0.132 ± 0.17	0.0132 ± 0.017	7.8 ± 1.5
15°	0.306 ± 0.17	0.0306 ± 0.017	6.28 ± 1.1
30°	1.23 ± 0.14	0.123 ± 0.014	3.77 ± 0.2
45°	1.83 ± 0.14	0.183 ± 0.014	3.06 ± 0.14
60°	2.67 ± 0.14	0.267 ± 0.014	2.38 ± 0.093
75°	3.22 ± 0.034	0.322 ± 0.0034	2.04 ± 0.019
90°	3.43 ± 0.034	0.343 ± 0.0034	1.93 ± 0.018

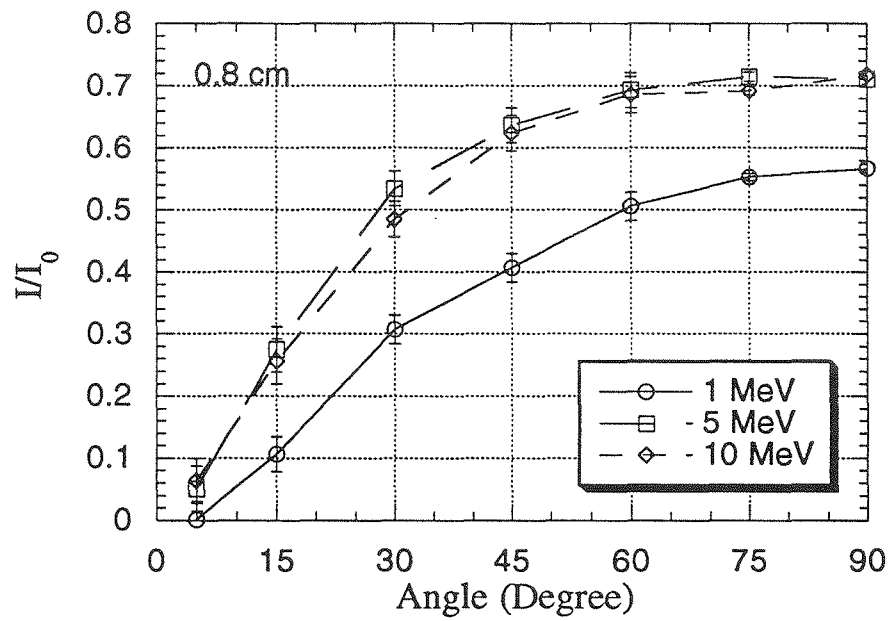


Figure 1 The normalized transmission of photons calculated with EGS4: 0.8 cm.

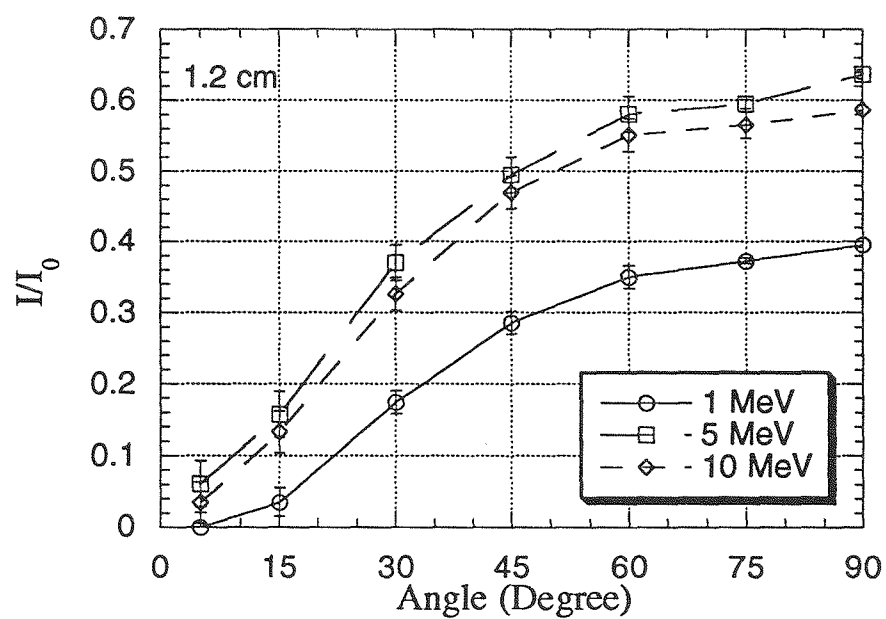


Figure 2 The normalized transmission of photons calculated with EGS4: 1.2 cm.

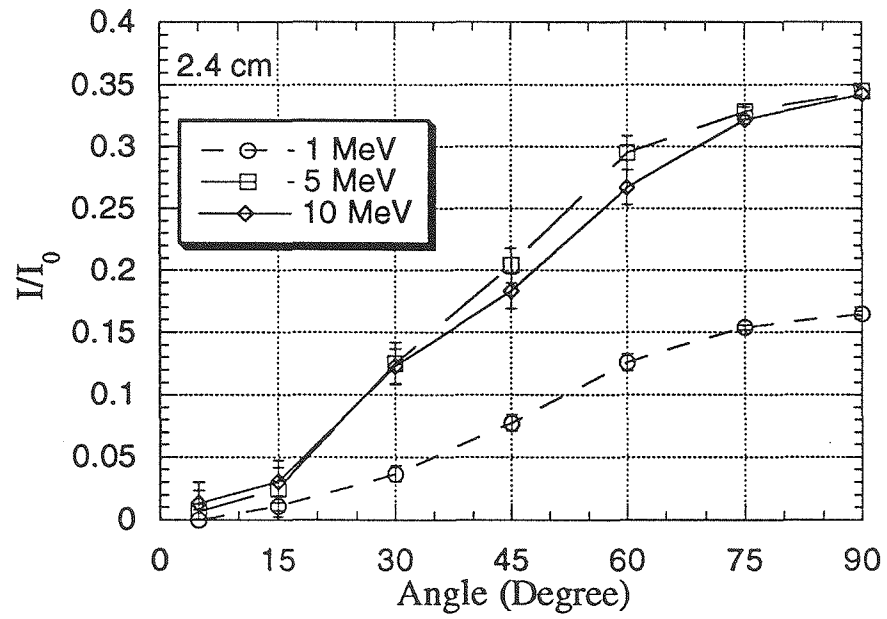


Figure 3 The normalized transmission of photons calculated with EGS4: 2.4 cm.

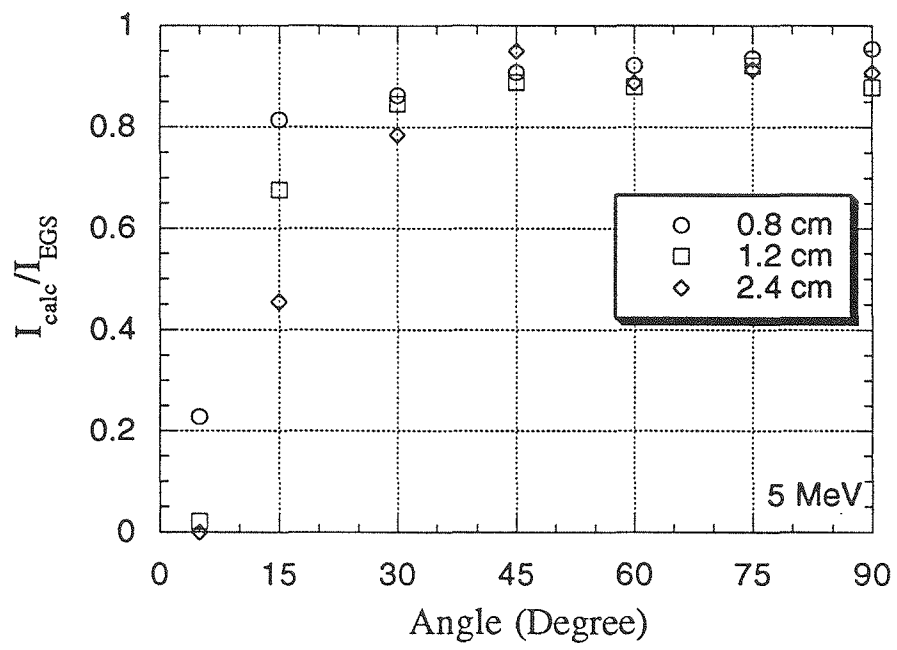


Figure 4 A comparison of the EGS4 results to transmission values obtained using a simple absorption calculation.